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MULTI-AREA LOAD FREQUENCY CONTROL (LFC) FOR POWER SYSTEM USING LINEAR QUADRATIC GAUSSIAN (LQG) CONTROLLER

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ABSTRACT:

Nowadays power demand is increasing continuously and the biggest challenge for the power system is to provide good quality of power to the consumer under changing load conditions. When real power changes, system frequency gets affected while reactive power is dependent on variation in voltage value. That is why real and reactive power is controlled separately. For satisfactory operation, the frequency of power system should be kept near constant value. Continuous change in frequency by variation of load is a big challenge for the generating unit to compensate it as quickly as possible. Many techniques have been proposed to obtain constant value of frequency and to overcome any deviations. The Load Frequency Control (LFC) is used to restore the balance between load and generation by means of speed control. The main goal of Load Frequency Control (LFC) is to minimize the frequency deviations to zero. Load Frequency Control (LFC) incorporates an appropriate control system, which is having the capability to bring the frequencies of the Power system back to original set point values or very near to set point values effectively after the load change. This can be achieved by using conventional controller but the conventional controller is very slow in operation. Modern and optimal control systems enjoy a lot of advantages over conventional controllers. They are much faster than conventional controller and give better stability response than conventional controllers. In this research paper, Linear Quadratic Regulator (LQR) and Linear Quadratic Gaussian Controller (LQR+ Kalman Filter) are applied for two areas Load Frequency Control (LFC) in power system using MATLAB/SIMULINK software package. Reduction in settling time and frequency deviation was successfully achieved by Using Linear Quadratic Gaussian (LQG) Controller.

Keywords:

Load Frequency Control (LFC), Conventional Controller, Linear Quadratic Regulator (LQR), Kalman Filter, Linear Quadratic Gaussian (LQG) Controller.

1. INTRODUCTION:

Power system is used for the conversion of natural energy to electric energy. For the optimization of electrical equipment, it is necessary to ensure the electric power quality. During transmission, both the active and reactive power balance must be maintained between the generation and utilization. When either frequency or voltage changes equilibrium point will shift. Good quality of electrical power system demands that both the voltage and frequency to be fixed at desired values irrespective of

change in loads that occur randomly. It is in fact impossible to maintain both active and reactive power without control which would result in variation of voltage and frequency levels. To cancel the effect of load variation and to keep frequency and voltage level constant, a control system is required. The active and reactive powers have a combined effect on the frequency and voltage. Frequency is mostly dependent on the active power and voltage on reactive power. Thus the issue of controlling power systems can be separated into two independent problems.[1] The active power and frequency control is referred to as Load Frequency Control (LFC). LFC is a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality. With an increasing demand, the electric power system becomes more and more complicated. The power system is subjected to local variations of load in random magnitude and duration. As the load varies, the frequency related with this area is affected. Frequency transients must be eliminated as soon as possible. The generators in a control area always vary their speed (speed up or slow down) for maintaining the frequency and the relative power angle to the predefined values with tolerance limit in both static and dynamic conditions. Frequency should remain nearly constant for satisfactory operation of power system. Frequency deviation can directly impact on a power system operation, system reliability and efficiency. Large frequency deviations can damage equipment and degrade load performance. Overload can ultimately lead to a system collapse.[2] Variation in frequency adversely affects the operation and speed control of induction and synchronous motors. Various control strategies have been proposed and investigated by several researchers for LFC design in power systems. Many classical approaches have been used to provide supplementary control which will drag the frequency to normal operating value within very short time. This extensive research is due to the fact that LFC constitutes an important function of power system operation where the main objective is to keeping the frequency fluctuations with in pre-specified limits.[3] In this research Paper, Linear Quadratic Regulator (LQR) and Linear Quadratic Gaussian Controller (LQG) are applied for two areas LFC in power system. Reduction in settling time and frequency deviation is successfully achieved by Using LQG Controller.

2. BRIEF LITERATURE SURVEY:

Pradipkumar Prajapati has presented various Conventional controllers for Multi Area Load Frequency Control in the power system. A comparison was made between PID controller and PI controller in terms of performance aspect in multi areas power systems. Simulation results showed that the PID controller outperformed the PI controller in terms of less frequency deviation and settling time.[1] Gajendra Singh Thakur used PI and PID controller to solve the Load Frequency Control problem of single area power system. Simulation results show that PID controller has better performance than the PI controller because it reduced the settling time and minimized overshoot. PID controller with simple approach can provide better performance comparing with the conventional PI controller. Simulation results show that the superior performance of the system using Z-N Tuned PID controller.[2] Mohinder Pal used PI controller for Load Frequency Control in the power system. It is seen that Integral Controller results in a stable frequency. With the proper choice of control parameters, frequency deviations can be effectively controlled. Due to disturbances in the power system frequency deviates. To overcome this problem Integral Controller is used.[3] Mohammed Wadi presents the analysis of an optimal LQR controller and Legendre Wavelet Function. A comparison was made between an LQR optimal controller and an optimal controller based on Legendre Wavelet Function in

terms of performance in single area power systems. Simulation results showed that the optimal controller based on Legendre wavelet function approximation method outperformed the LQR controller in terms of less frequency deviation and steady state error; while both had the same settling time. A numerical example demonstrated the effectiveness of the proposed optimal control via Legendre Wavelets Function over LQR controller.[4]

3. LOAD FREQUENCY CONTROL:

In a large electrical power system, nominal frequency depends significantly on the balance of produced and consumed active power. As the peak demands do not have any certain time, they may occur at any random time of the day in the power system. When active power imbalance occurs in any part of the system, it results in changes in the frequency of the entire system. If there is any sudden load change occurring in a control area of power system, then there will be frequency deviation. The generators in a control area always vary their speed together (speed up or slow down) for maintaining the frequency to the predefined values with tolerance limit in both static and dynamic conditions.[4] The main objective of LFC is to maintain the frequency constant by means of speed control. Industrial loads connected to electrical power system are very sensitive to the quality of electrical energy, mainly the frequency component. Thus, the steady-state frequency error in the system must stay within acceptable values in order to keep the balance. Figure 1 shows the relationship between system frequency and load which is inversely proportional.[8]

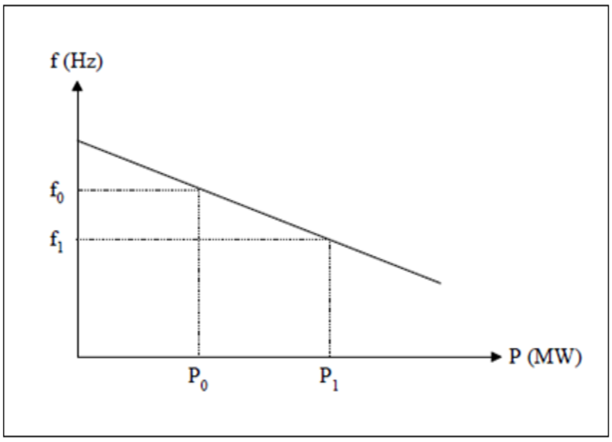

FIGURE 1: VARIATION OF LOAD FREQUENCY CHARACTERISTIC

Possible increase in load reduces the nominal frequency of the system. This alternation in frequency is sensed by a regulator in the primary control loop; subsequently, the rotational speed of the turbine is increased leading to an increase in the produced power.[5] Frequency deviations can directly impact power system operation, system reliability and efficiency. Large frequency deviations can damage equipment, degrade load performance, overload transmission lines and adversely affect the performance of system protection schemes. These large-frequency deviation events can ultimately lead to a system collapse. Variation in frequency adversely affects the operation and speed control of induction and synchronous motors. Due to dynamic nature of the load, continuous load change cannot be avoided but the system frequency can be kept within sufficiently small tolerance levels by adjusting the generation continuously using LFC.[8] Figure 2 gives the schematic diagram of load frequency control for power system. In this control method, a frequency sensor senses the change in frequency and gives the signal Δf. The LFC senses the change in frequency signal and the increments real powers ΔP, which will indirectly provide information about incremental state error. These sensor signals are amplified, mixed and transformed into a real-power control signal ΔPc. The valve control mechanism

takes ΔPc as the input signal and provides the output signal, which will change the position of the inlet valve of the prime mover.[6]

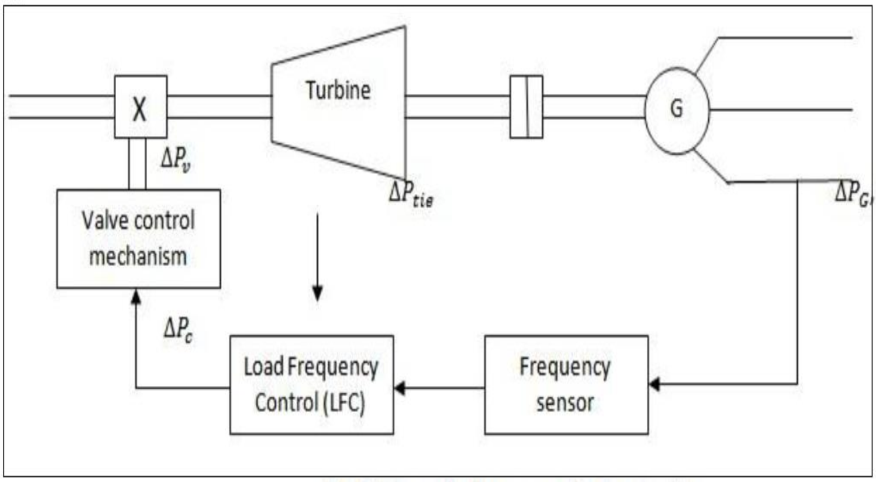

FIGURE 2: BLOCK DIAGRAM OF LOAD FREQUENCY CONTROL (LFC) FOR POWER SYSTEM. [8]

4. LINEAR QUADRATIC REGULAOR (LQR) CONTROLLER:

This is a technique that is applied in the control system design which is implemented by minimizing the Performance Index of the system variables. Here we have discussed the design of the optimal controllers for the linear systems with Quadratic Performance Index, which is also known as the Linear Quadratic Regulator or LQR Controller. The aim of the optimal regulator design is to obtain a control law u*(x, t) which can move the system from its initial state to the final state by minimizing the Performance Index. The Performance Index is selected to give best trade-offs between performance and cost of control. The Performance Index which is widely used is the Quadratic Performance Index and is based on minimum error and minimum energy criteria.[7-8]

Consider a plant:

$$X(t) = Ax(t) + Bu(t) \qquad (1)$$

The aim is to find the Vector K of the control law,

$$U(t) = -K(t)*x(t) \qquad (2)$$

It minimizes the value of the Quadratic Performance Index J of the form,

$$J = \int_{to}^{t} (x'Qx + u'Ru)dt \qquad (3)$$

Where Q is a positive semi definite matrix and R is real symmetric matrix. The choice of the elements of Q and R allows the relative weighting of individual state variables and individual control inputs.[9]

To obtain the solution we make use of the method of Langrange Multipliers. The problem reduces to the minimization of the following unconstrained Equation,

$$L[x, \lambda, u, t] = [x'Qx + u'Ru] + \lambda'[Ax + Bu - \dot{X}] \qquad (4)$$

The optimal values determined are found by equating the partial derivative to zero.

$$\frac{dL}{d\lambda} = AX^*+BU^*-\dot{X}^*= 0 \qquad , \qquad X^* = AX^*+ BU^*$$

$$\frac{dL}{du} =2RU^* + \lambda'B =0 \qquad , \qquad U^* = \frac{-1}{2}R^{-1}\lambda'B$$

$$\frac{dL}{dx} =2X'Q+ \lambda'+\lambda'A =0 \qquad , \qquad \dot{\lambda} = -\dot{2}QX^*-A'\lambda$$

Assume that there exists a symmetric, time varying positive definite matrix P (t) satisfying,

$$\lambda =2P(t)X^* \qquad (5)$$

Substituting Equation 2 into (U^*) gives the optimal closed-loop control law,

$$U^*(t) = -R^{-1}B'P(t)X^* \qquad (6)$$

Obtaining the derivative of Equation 5,

$$\dot{\lambda}=2(\dot{P}X^*+P\dot{X}^*) \qquad (7)$$

By using equation 7 and $\dot{\lambda}$, we obtained,

$$P(t) = -P(t)A - A'P(t) - Q+ P(t)BR^{-1}B'P \qquad (8)$$

The above equation is referred to as Matrix Riccati Equation. For linear time invariant systems, since $\dot{P}$=0, when the process is of infinite duration tf =∞ and Equation 8 becomes,

$$PA + A'P(t) + Q - PBR^{-1}B'P=0 \qquad (9)$$

One of the important properties of LQ-Regulators is that they guarantee nominally stable closed-loop system, provided certain conditions are met.[8]

The MATLAB Control System toolbox can be used for the solution of the Riccati Equation. Choosing the weight matrices Q and R usually involves some kind of trial and error and they are usually chosen as diagonal matrices.[10] The solution of LQR results in an asymptotically stable closed-loop system if,

1. The system (A, B) is controllable.
2. R>0
3. $Q=C^TC$ Where (C, A) is observable.

The definition of optimal control system is designing the control law in order to find out the feedback gain matrix 'K' such that the given Performance Index will be minimized. The LQR design procedure is in stark contrast to classical control design, where the gain matrix K is selected directly.[6] To design the optimal LQR, the design engineer first selects the design parameter weight matrices Q and R. Then, the loop time response is found by simulation. If this response is unsuitable, new values of Q and R are selected and design is repeated. The parameter weight matrices Q and R can be written as,[9]

$$Q=C^TC \quad , \quad R=1 \qquad (10)$$

The MATLAB code is written in MATLAB-R2011. The MATLAB command to obtain feedback K-Matrix is,[8]

$$[K, P]=lqr2(A, B, Q, R) \qquad (11)$$

The optimal gain vector K for Area 1 & Area 2 in Power system for LFC is obtained by using Equation 11,

Feedback K-Matrix of Area1=K_1= [-0.086 -0.507 -0.909]

Feedback K-Matrix of Area2=K_2= [-0.077 -0.529 -0.914]

5. KALMAN BUCY FILTER:

The LQR solution is basically a state-feedback type of controller which requires that all the states must be available for feedback. Designing a control system is required for estimating the state vector, based upon a measurement of the output given by equation 12 & 13 and known input u. This optimal observer is commonly known as Kalman Filter. In addition, the combination of state feedback and Kalman observer will always result in stable closed loop systems. The Kalman Filter provides us with a procedure of designing observers for multivariable plants. This observer is guaranteed to be optimal in the presence of noise signal. Consider a plant with the following state space representation.[9]

$$\dot{X}= AX + BU + \omega \qquad (12)$$

$$Y = CX + DU + v \qquad (13)$$

Where,

A, B, C are the plant's state coefficient matrices.

ω is the process noise vector.

v is the measurement noise vector.

The state space solution of the above equation was first provided by R.E.Kalman and R.S Bucy.

The Optimal observer (Kalman Filter) is given by,

$$\dot{\hat{X}} = A\hat{X}+BU+L(Y-C\hat{X}) \qquad (14)$$

Where $\hat{X}$ is the estimate of state x and L is the gain matrix of Kalman Filter. The observer gain L is computed as,

$$L=\sum C^T R^{-1} \qquad (15)$$

The $\sum$ is found as the positive semi-definite solution of,

$$A\sum+ \sum A' + Q - \sum C^T R^{-1} C\sum=0 \qquad (16)$$

The Equation 16 is very similar to the LQR solution known as Riccati Equation. The Q and R matrices represent the intensity of the process and sensor noise input and it can be selected by the user. These matrices are known as co-variance matrices. Their size is a measure of how strong the noise is: the larger the size, the more random or intense the noise hence it is called the noise intensity. Finally the mathematical condition for the design of Kalman Filter is that the matrices Q and R are positive semi definite and the system must be observable. [9]

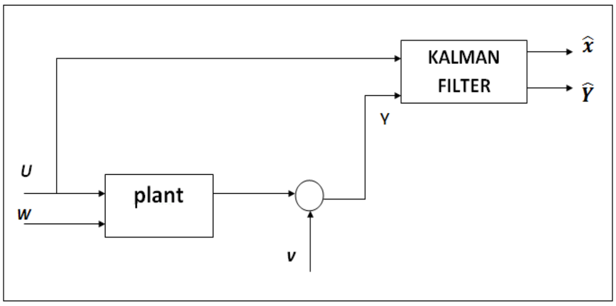

FIGURE 3: BLOCK DIAGRAM OF KALMAN FILTER FOR LFC. [9]

The Kalman filter Optimal Gain Matrix L is calculated with W and V matrices at the nominal operating point as follow,[5]

$$W=10*B^T*B \qquad (17)$$

$$V=0.01*C*C^T \qquad (18)$$

The MATLAB code is written in MATLAB-R2011. The algebraic Riccati Equation can be solve using the specialized Kalman Filter MATLAB command lqe .The MATLAB command to obtained observer gain L of Kalman Filter is given by,[5]

$$[L, S] = \text{lqe}\ (A, B, C, W, V) \qquad (19)$$

Where,
L is the returned Kalman Filter optimal gain.
S (∑) is the returned solution to the Riccati Equation.
The observer gain L of Kalman Filter for Area 1 & Area 2 in Power system for LFC is obtained by using Equation 19,

$$\text{L-Gain of Kalman Filter for Area 1}=L_1= \begin{bmatrix} -4.9329 \\ -0.0162 \\ 939.230 \end{bmatrix}$$

$$\text{L-Gain of Kalman Filter for Area 2}=L_2= \begin{bmatrix} -4.366 \\ -0.0150 \\ 673.4705 \end{bmatrix}$$

6. LINEAR QUADRATIC GAUSSIAN (LQG) CONTROLLER:

LQR was designed which is the cause of minimization of the Quadratic Objective Function. The Kalman Filter was also introduced with LFC in presence of noise process w and measurement noise v.[10] The combination of LQR with the Kalman Filter forms an Optimal Compensator which is called as Linear Quadratic Gaussian (LQG) Controller. The optimal compensator design process is the following, [5]

1. Design an optimal regulator (LQR) for a linear plant using full-state feedback. The regulator is designed to generate a control input U (t), based upon the measured state-vector X.
2. Design Kalman Filter for the plant assuming a known control input U (t) a measured output Y(t) including noises w & v.
3. Combine the separately designed optimal regulator and Kalman Filter into an optimal compensator that generates the input vector U (t), based upon the estimated state-vector $\widehat{X}$ rather than the actual state vector X, and the measured output Y (t). The plant equation and the problem solution is now repeated. [5]

$$\dot{X} = AX + BU + \omega \qquad (20)$$

$$Y = CX + v \qquad (21)$$

The Control-Law of LQR is now given by,

$$U(t) = -K(t) * \hat{X}(t) \qquad (22)$$

The Kalman Filter state-space equation is given by,

$$\dot{\hat{X}} = A\hat{X} + BU + L(Y - C\hat{X}) \qquad (23)$$

By putting Equation 22 of LQR in Equation 23 of Kalman Filter, the state-space equation of LQG-Controller is given by,

$$\dot{\hat{X}} = (A - B*K - L*C + L*D*K)*\hat{X} + L*Y \qquad (24)$$

Where,

K & L are the optimal regulator and Kalman Filter gain.

$\hat{X}$ is the estimated state vector.[9]

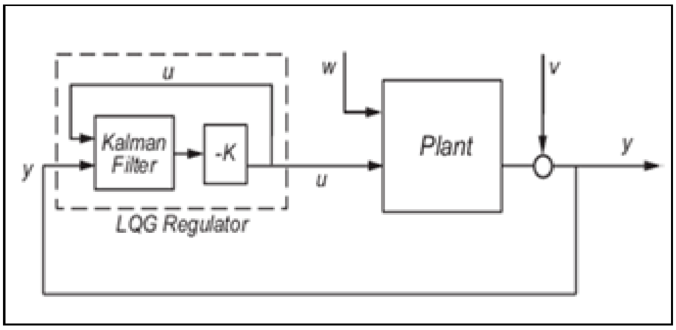

FIGURE 4: BLOCK DIAGRAM OF LQG-CONTROLLER FOR LFC. [5]

Using MATLAB's Control System Toolbox, a state-space model of the closed-loop system, can be constructed as follows.[5]

Sysp =ss (A, B, C, D); (25)
sysc = ss (A-B*K-L*C+L*D*K ,L,K ,zeros (size (D'))) (26)
syscl = feedback(sysp,sysc); (27)

Where,

sysp = State-space model of the plant (LFC).

Sysc= State-space model of the LQG compensator.

syscl = State-space model of the closed loop system.

7. SIMULATION AND RESULTS :

A comparison of LFC (uncompensated) without any controller, with LQR Controller and finally with LQG Controller has been observed. The comparison is made in terms of performance with respect to frequency deviation and settling time as shown in Table 1. The parameters of the numerical example, is solved using MATLAB as shown in Table 2. In addition, the solution of an example consists of three scenarios with LFC: the first one contains no controller (uncompensated LFC), the second scenario used LQR Controller and finally the last scenario used LQG Controller.

A. FIRST SCENARIO:

In the first scenario, MATLAB simulation of Load Frequency Control (LFC) is constructed using Simulink and solved without using any controller. Figure 5 and Figure 6 show the Simulink diagram of LFC and the frequency deviations respectively,

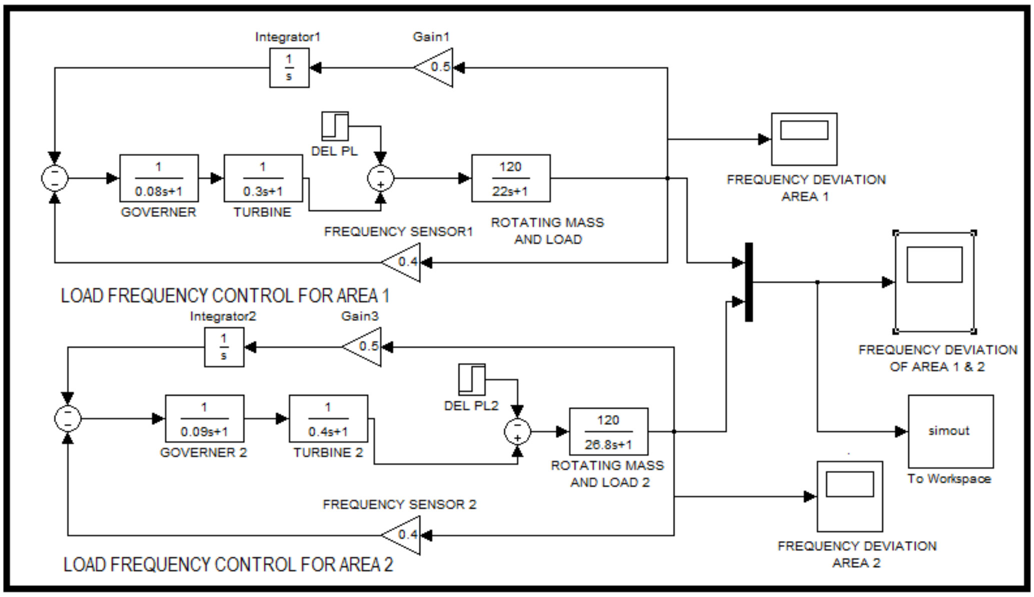

FIGURE 5: SIMULINK MODEL OF FIRST SCENARIO FOR TWO AREA LFC WITHOUT ANY CONTROLLER.

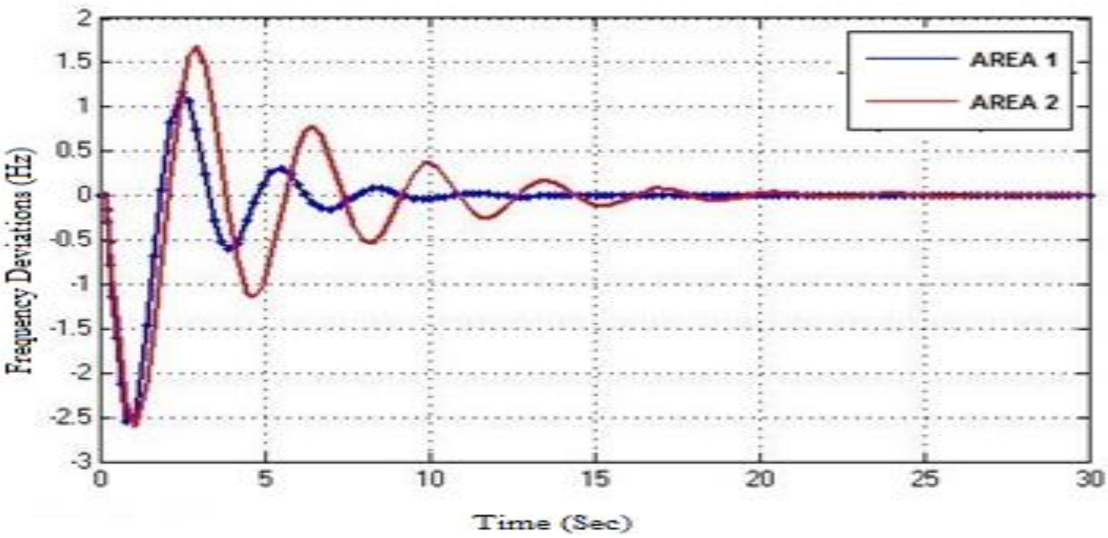

FIGURE 6: FREQUENCY DEVIATION OF FIRST SCENARIO FOR TWO AREA LFC WITHOUT ANY CONTROLLER. (UNCOMPENSATED LFC)

B. SECOND SCENARIO:

In the second scenario, LQR optimal controller is designed in which K-gain vector is used as a feedback to reduce the frequency deviations and settling time of LFC in the power system. The LQR controller is designed using Equation 11 in M-file and by using Simulink in MATLAB. The simulink diagram and the frequency deviations are shown in Figures 7 and 8 respectively,

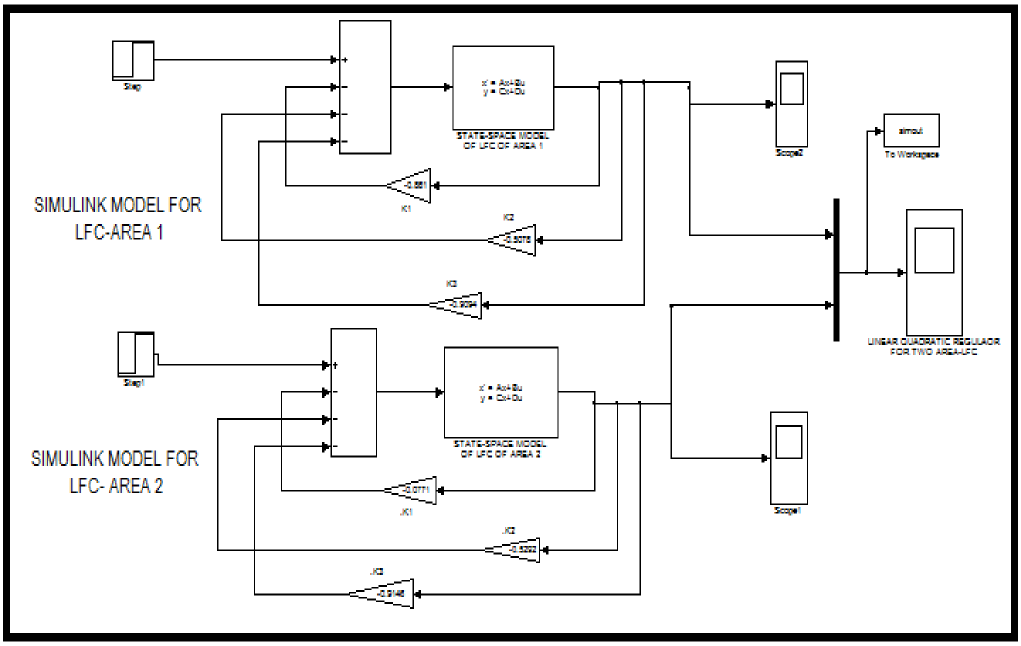

FIGURE 7: SIMULINK MODEL OF SECOND SCENARIO FOR TWO AREA LFC WITH LQR_CONTROLLER.

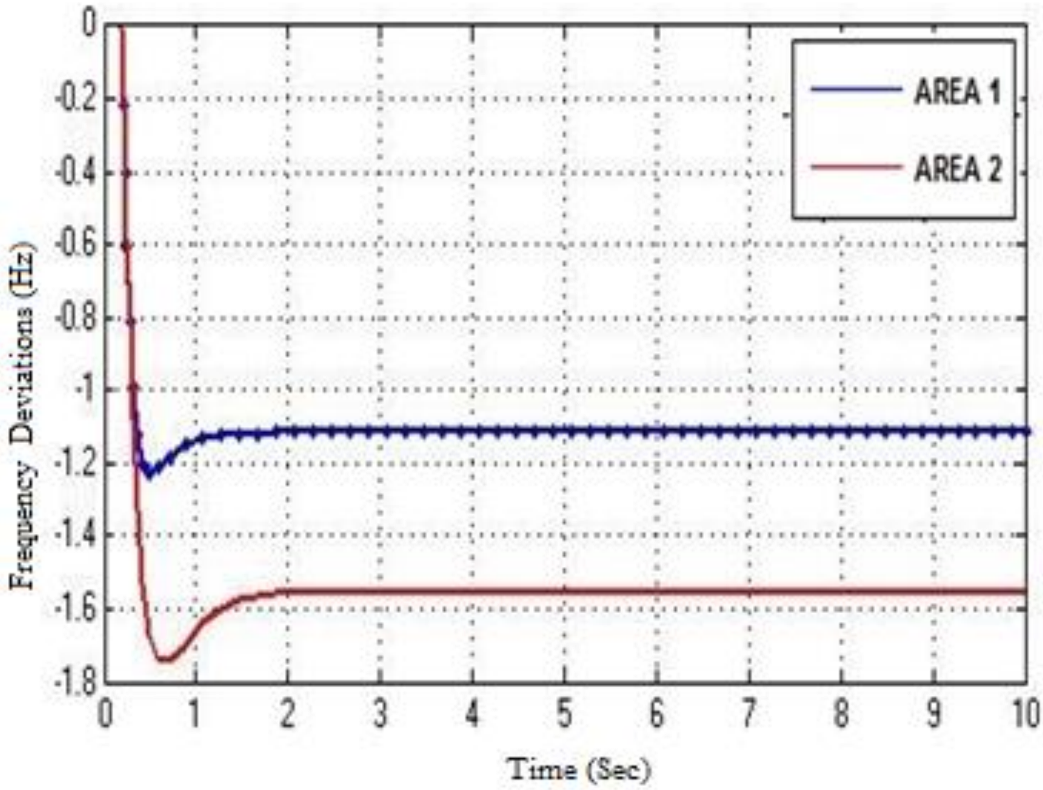

FIGURE 8: FREQUENCY DEVIATION OF SECOND SCENARIO FOR TWO AREA LFC WITH LQR _CONTROLLER.

C. THIRD SCENARIO:

In the final scenario, the LQG Controller is designed which is used as a feedback in two area of LFC, to reduce the frequency deviations and settling time in power system. The LQG controller is designed

using Equations 25 to 27 in M-file and MATLAB. The frequency deviation is shown in Figure 9 respectively,

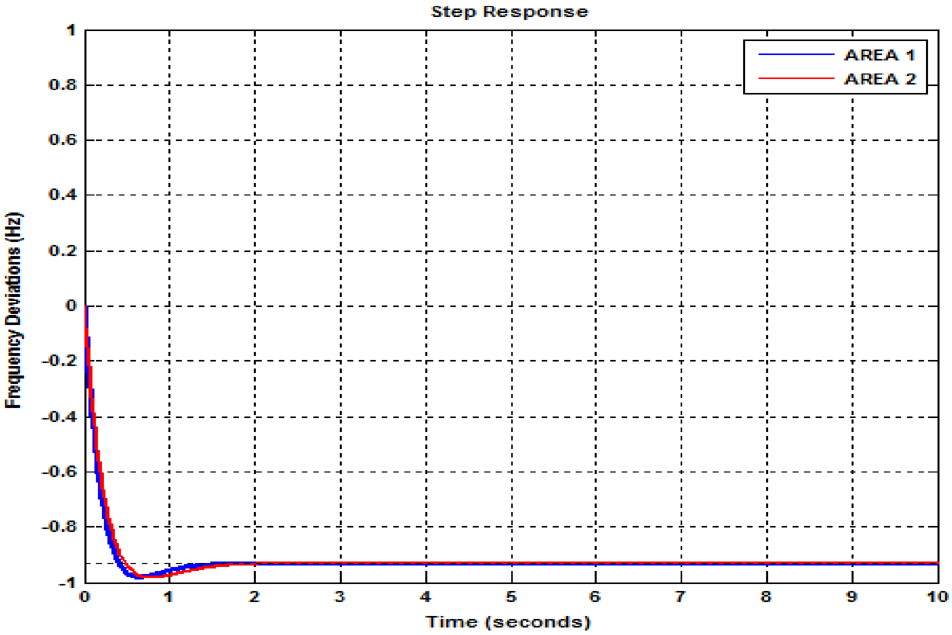

FIGURE 9: FREQUENCY DEVIATION OF THIRD SCENARIO FOR TWO AREA LFC WITH LQG_CONTROLLER.

8. DISCUSSION

Table 5.1 shows the performance of LFC by various control strategy over frequency deviations and settling time for two area LFC in power system.

S #	PARAMETER	AREA	UNCOMPENSATED LFC	LFC WITH LQR_CONTROLLER	LFC WITH LQG_CONTROLLER
1	FREQUENCY DEVIATION (Hz)	1	1.1 to -2.5	0 to -1.23	0 to -0.9
		2	1.5 to -2.5	0 to -1.7	0 to -0.98
2	SETTLING TIME (Sec)	1	11 Sec	1.5 Sec	1.1 Sec
		2	21 Sec	2 Sec	1.38 Sec

TABLE 1: COMPARATIVE ANALYSIS OF DIFFERENT CONTROLLERS WITH LOAD FREQUENCY CONTROL (LFC) IN POWER SYSTEM.

In this research paper, first an optimal LQR Controller is designed for LFC in the power system. Then the states are estimated by Kalman Filter. Then, by combining both LQR and Kalman Filter an optimal compensator called Linear Quadratic Gaussian (LQG) is designed which recovers the responses of optimal LQR-regulator in the presence of estimated states. The performance of LQR and LQG Controllers are shown in the above simulations of Figure 8 & 9. From the above simulations, it is clear that the LFC without any controller has more frequency deviations as compare to LQR and LQG controllers. It is clear from the graphical representation of the step response that the settling time is

more in an uncompensated system than that for a compensated system while using LQR and LQG controllers and the system reached faster to a steady state in compensated system with these advance control techniques.

9. CONCLUSION

This research paper contains designing of a controller that can produce optimal results with LFC in power system. Two Controllers with LFC were studied into account. It was seen that a feedback controller called LQR Controller with LFC was better than the uncompensated system in terms of frequency deviation and settling time. The Linear Quadratic Gaussian (LQG) Controller is designed to provide the best results in terms of both frequency deviation and settling time and achieved required reliability under changing load conditions.

10. FUTURE WORK

1. The parameters in this research work were taken as constant throughout the whole operation, but there may be parameter uncertainty due to wear and tear, temperature Changes, imperfection of component, aging effect and environment changes etc. So, during controller designing, variation of these parameters may be taken in to consideration.

2. The LFC for Power System can be designed by using PID controller via different optimization techniques, like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA) and Artificial Neural Network (ANN) etc and results can be compare with Linear Quadratic Gaussian (LQG) Controller.

11. APPENDIX

S #	TWO AREA POWER SYSTEM PARAMETER
1	F=50Hz
2	D=8.34e-3
3	Kr_1=0.5
4	Kr_2=0.4
5	Tr_1=10.0s
6	Tr_2=11.0s
7	Tg_1=0.08s
8	Tg_2=0.09s
9	Tt_1=0.3s
10	Tt_2=0.4s
11	H_1= 0.09166
12	H_2= 0.108033

TABLE 2: TWO AREA POWER SYSTEM PARAMETERS.

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